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Collisionless Electrostatic Shock Modeling and Simulation

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Overview

- Motivation and Background
- What is a Collisionless Shock Wave?
- Features of the Collisionless Shock
- The Shock Simulation Model
- Simulation Results and Verification
- Future Work

Background

Who am I?

- Grew up in Olympia, WA, The City of Champions
- B.S. Aerospace Engineering 2016 | UW, Seattle
- Start Graduate Program at UW Autumn 2016
- Hobbies:
  - Studying classical guitar,
  - Observing the sky,
  - Appreciating existence and nature.

Investigation Motivation

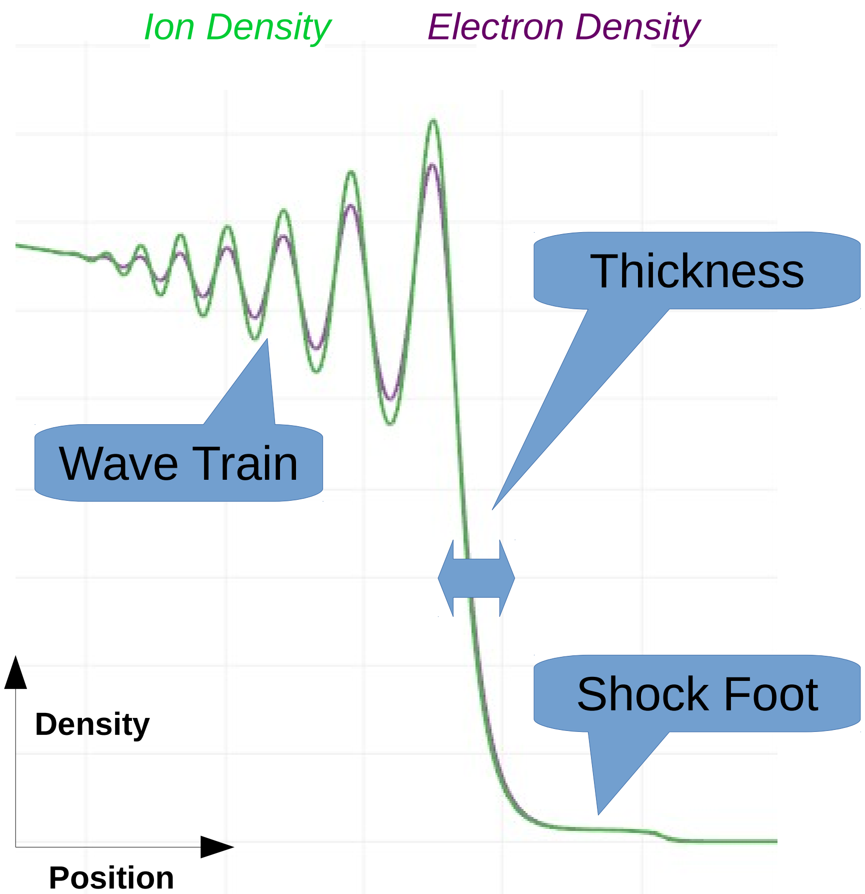
What's the Point?

- **The 1D Collisionless Ion-Acoustic Shock Wave:**
  - **Has a simple premise**
  - **Is rich in nonlinear effects difficult for theoretical prediction,**
    - **Wave Dispersion**
    - **Wave-Particle Interaction**
    - **Various Wave Dissipation Mechanisms**
  - **Shock structure is an active area of research. In particular,**
    - **Capacity to create ion beam of super-shock velocity.**
- **Validation of Simulation Frameworks**
  - **The shock is a model problem for simulation code validation.**

The Collisionless Shock Wave

<u>Electrostatic Shock Features</u>

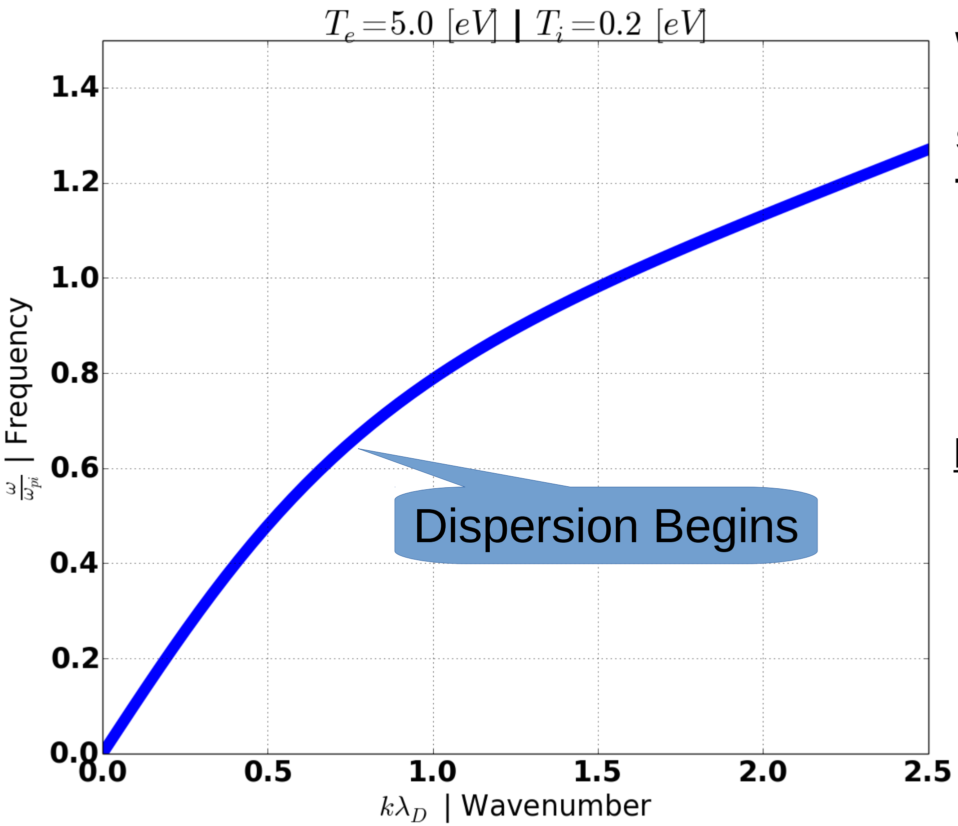
- Propagation occurs via collective electric interactions
- Shock front is dispersed across many Debye lengths
- Wave is accompanied by an electric field perturbation
- Two classes of shock:
  - <u>Subcritical</u>: M < M* ~ 1.8
    - Accompanied by undulating wave-train
  - <u>Supercritical</u>: M > M* ~ 1.8
    - Increase in dissipation
    - Reflects almost all ions



Details on Shock Structure

Shock Thickness

- Ion-acoustic dispersion relation predicts the electron contribution to acoustic speed to decay for wavelengths approaching the Debye length.
- Imagine shock formation: nonlinear steepening of an acoustic disturbance.



Wave steepening is balanced by dispersion;

short wavelength components recede from the wavefront.

$$t \approx k_D^{-1}$$

Linearized Ion-Acoustic Dispersion Relation

$$\left(\frac{\omega}{k}\right)^2 = \frac{1}{1+(k\lambda_D)^2}\frac{T_e}{m_i} + \gamma_i \frac{T_i}{m_i}$$

Details on Shock Structure

Wave Train Properties

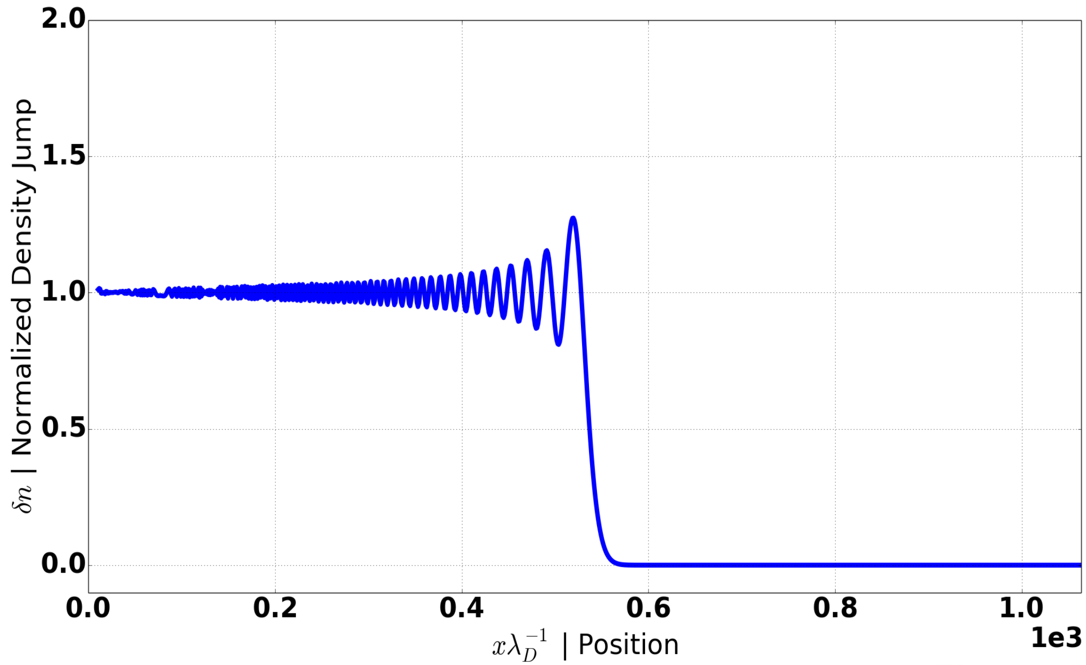
– **Linearized Model of Dispersive Shock, the Integrated Airy Function:**

- **Linearization of the fluid equations with piston-like boundary conditions gives a solution for the shock behavior.**
- **Assumes cold upstream ions, therefore neglecting shock reflection.**

$$n(x,t) = n_0 + \frac{\delta n}{2}\int_{\beta}^{\infty} Ai(\alpha)d\alpha$$

$$\beta = \left(\frac{2}{3}\right)^{\frac{1}{3}}\left(\frac{\lambda_D}{x}\right)^{\frac{1}{3}}\frac{(x - C_s t)}{\lambda_D}$$

$$C_s = \left(\frac{T_e}{m_i}\right)^{\frac{1}{2}}$$

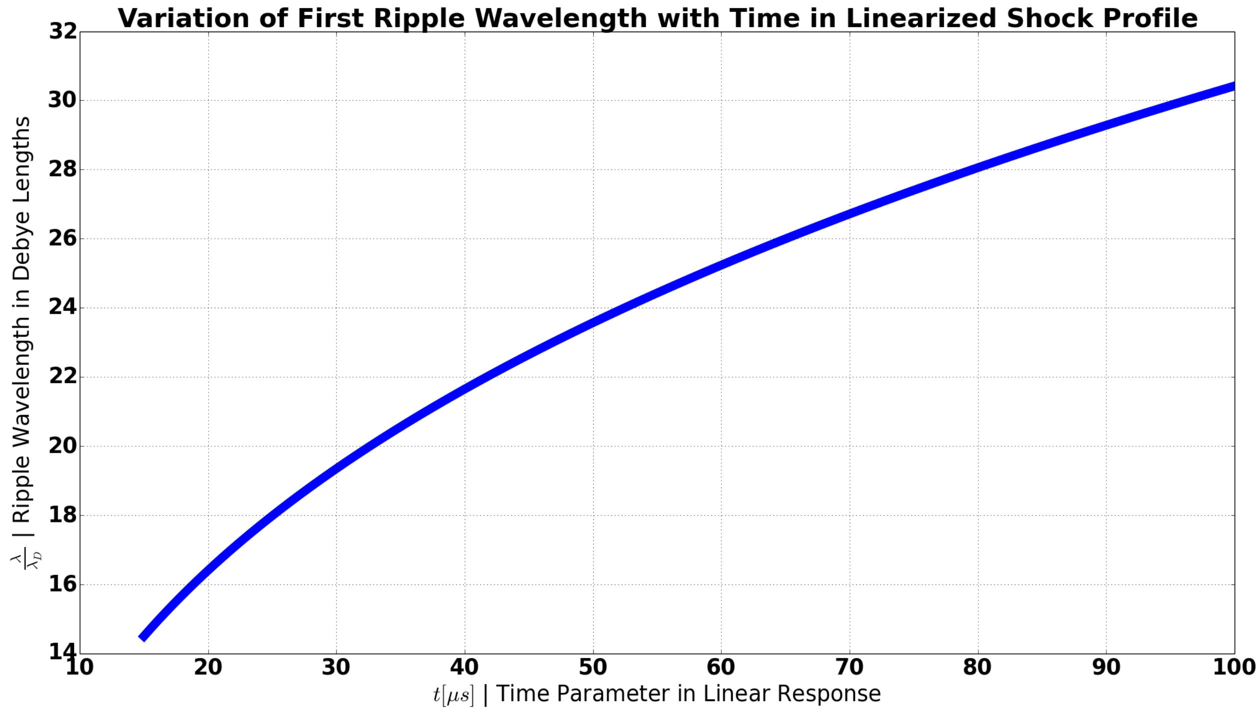


Details on Shock Structure

Wave Train Properties

– **Linear Model Predicts**:

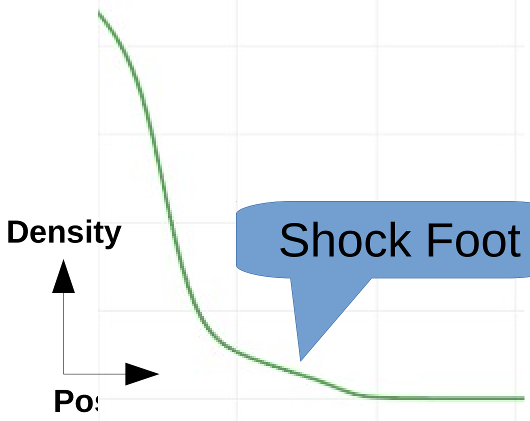
- **The wave train spreads out in time; peak-to-peak wavelength increases.**
- **No variation of non-dimensional wavelength with electron temperature.**
- **The wave train increases in frequency towards the back of the train.**

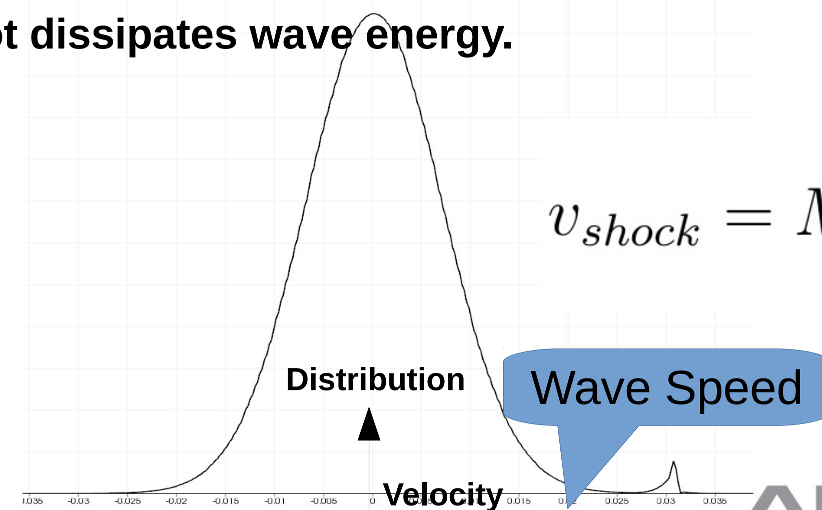


Details on Shock Physics

Sources of Collisionless Wave Dissipation

- **Landau Damping:**
  - **A form of wave-particle resonance. Resonant particles sap wave energy.**
  - **Damping is proportional to slope of distribution function at wave velocity.**
  - **Higher electron temperature means greater shock speed, so less damping.**
- **Ion Reflection / The Shock Foot:**
  - **Higher shock strength brings a greater potential difference.**
  - **Ions unable to traverse difference are reflected downstream.**
  - **Formation of the shock foot dissipates wave energy.**



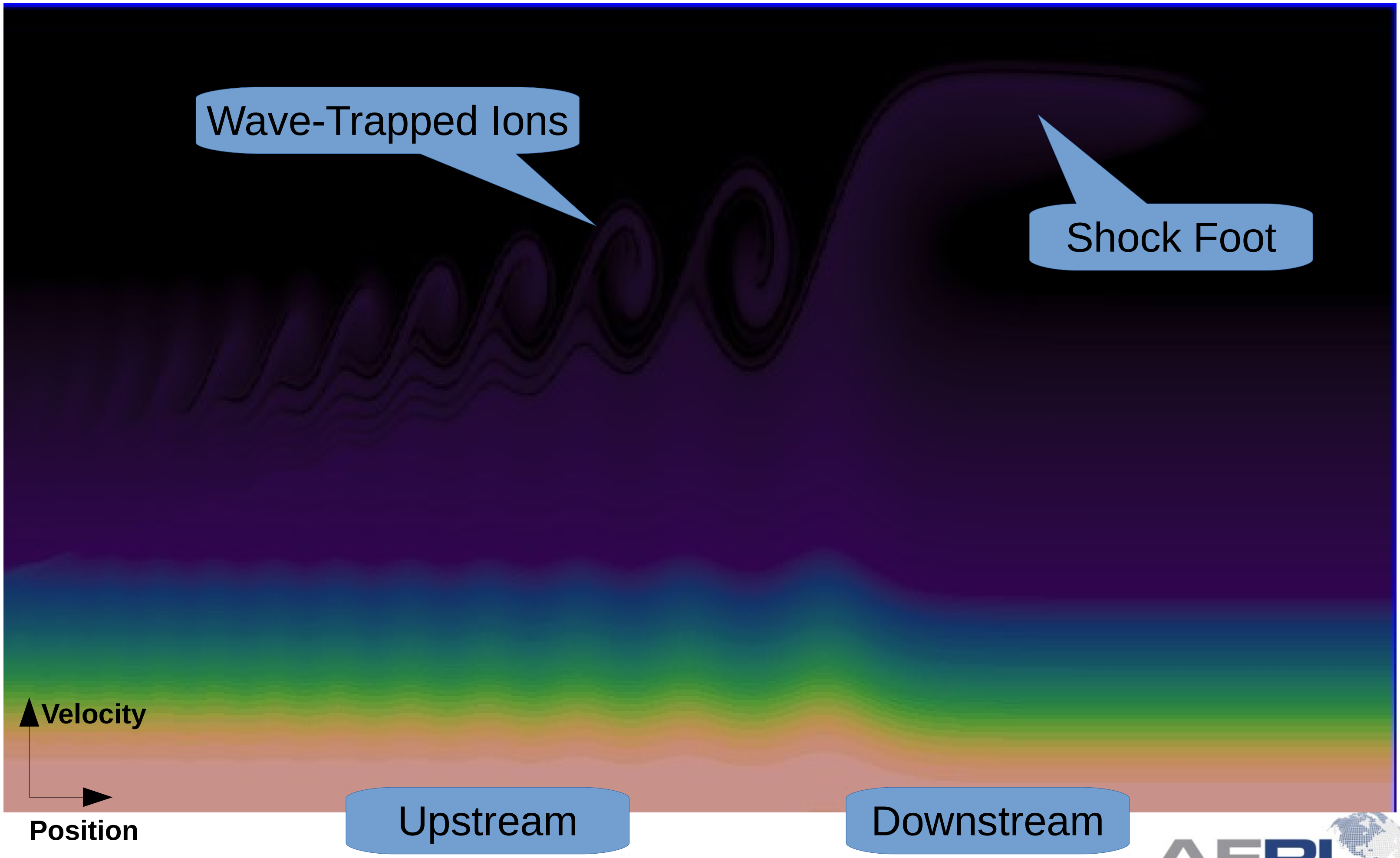


$$v_{shock} = M\sqrt{\gamma\frac{T_e}{m_i}}$$

Details on Shock Physics

Phase Space Indicators of Wave Dissipation

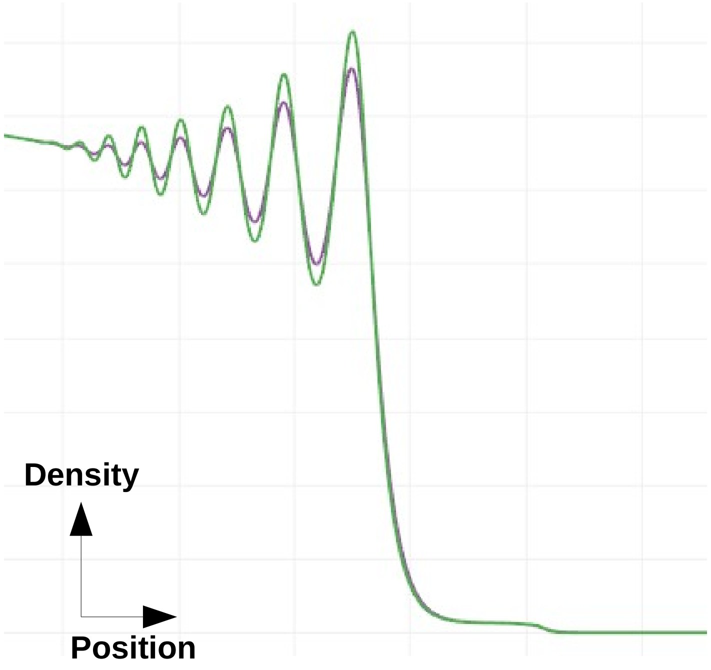
(Log View of Distribution)



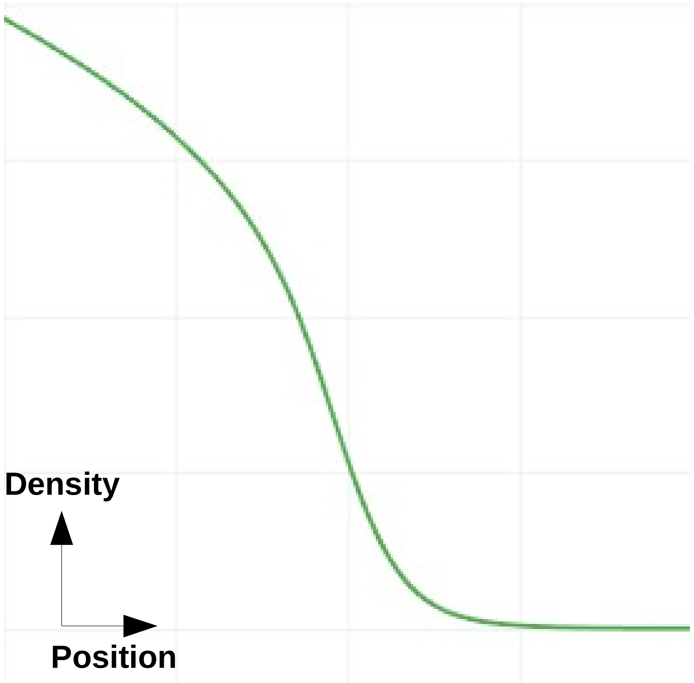
Dissipation Controls Wave Train

Under- and Over-damped Shocks

– **Under-damped**:
  - **Dissipation is weak, ripples persist.**
  - **High** $\frac{T_e}{T_i}$



– **Over-damped**:
  - **Strong dissipation damps ripples.**
  - **Low** $\frac{T_e}{T_i}$



The Simulation Model

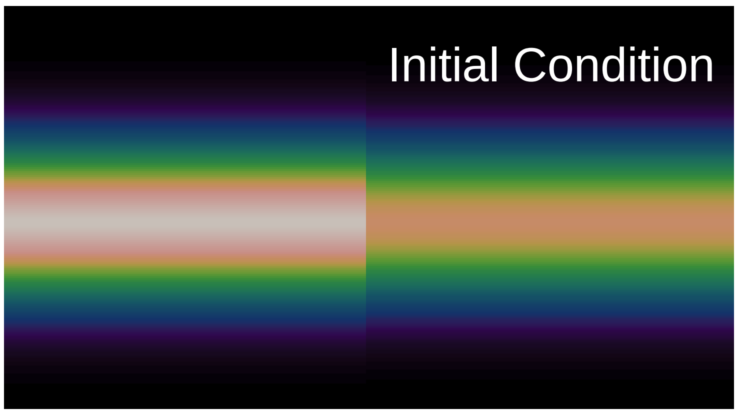
Initial Conditions: Ion-Acoustic Shock Tube

Shown: Velocity Distribution Function (VDF) $f(x, v)$
And Potential Profile $\phi(x)$

High Particle Density *Low Particle Density*

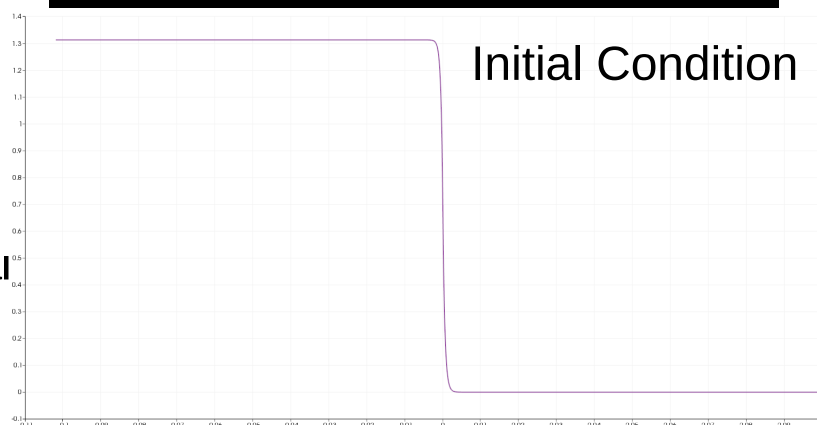
Velocity

Position



Potential

Position



Kinetic Model

Vlasov Equation $$\frac{\partial f}{\partial t} + v \cdot \frac{\partial f}{\partial x} - \frac{e\nabla\phi}{m} \cdot \frac{\partial f}{\partial v} = 0$$

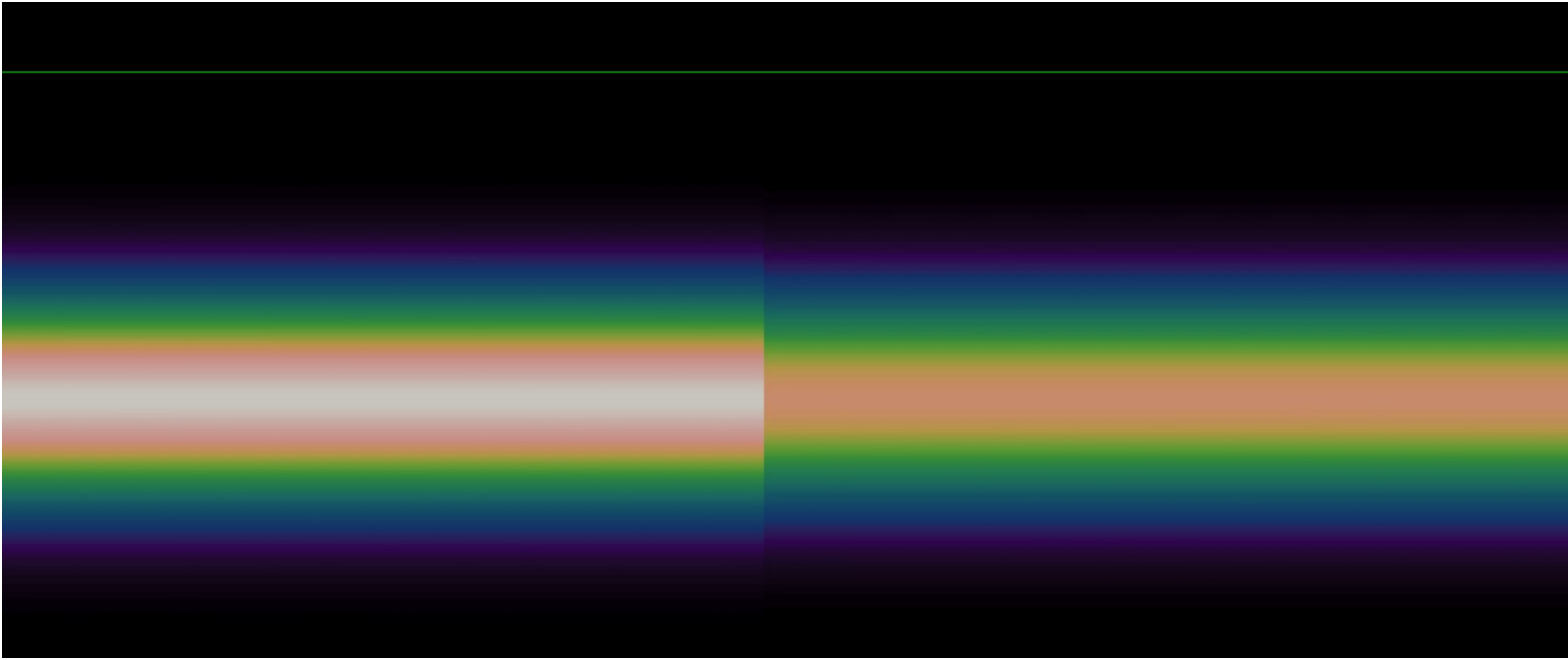
Poisson Equation $$\epsilon_0 \nabla^2 \phi + \rho = 0$$

Boltzmannian Electrons $$n_e = n_{ref} \cdot \exp \frac{\phi}{T_e}$$

Simulation Procedure:

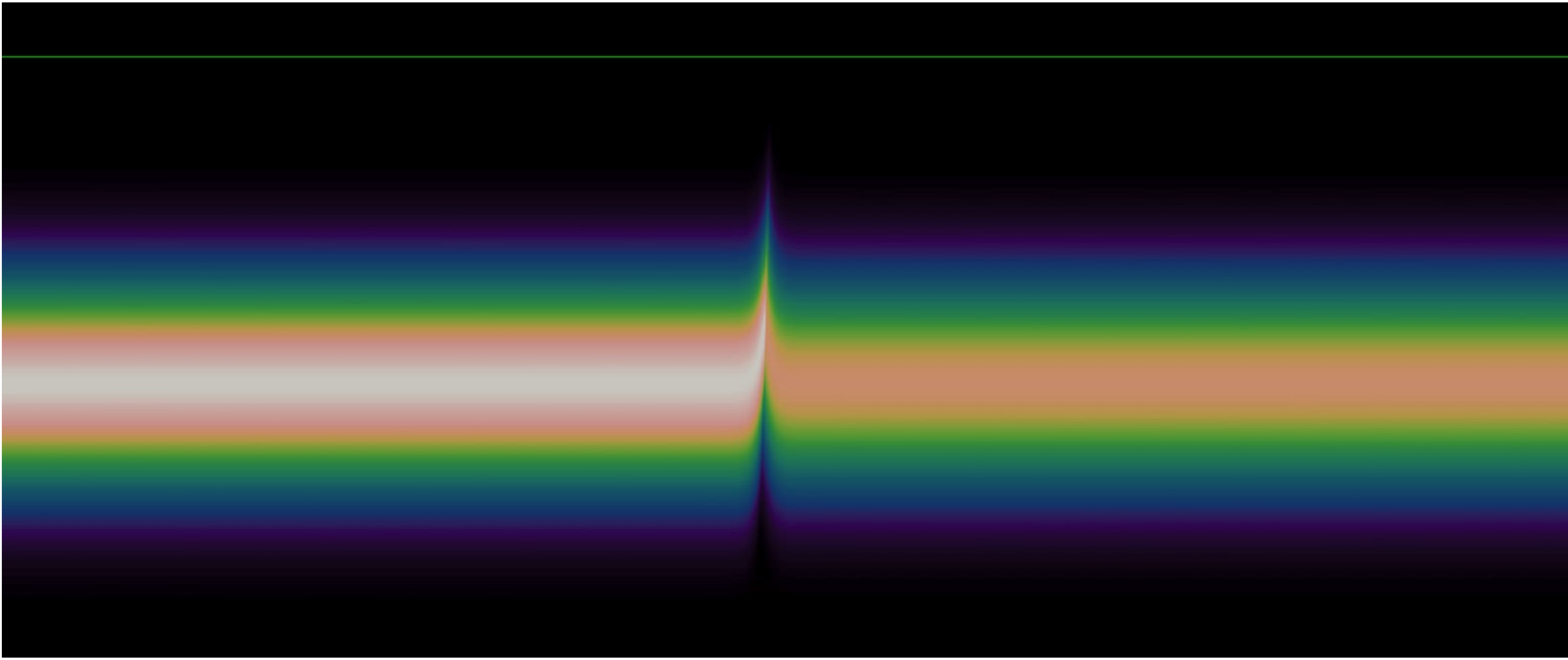
- **Solve Poisson's equation for potential.**
  - **VDF for ion density**
  - **Electron density from** $\exp \frac{\phi}{T_e}$
- **Update the distribution function via Vlasov equation.**
- **Repeat.**

Typical Simulation Result



Lightly Damped Case
Electron Temperature: 5 eV | (Te/Ti = 25)
Density Difference: 30%

Typical Simulation Result



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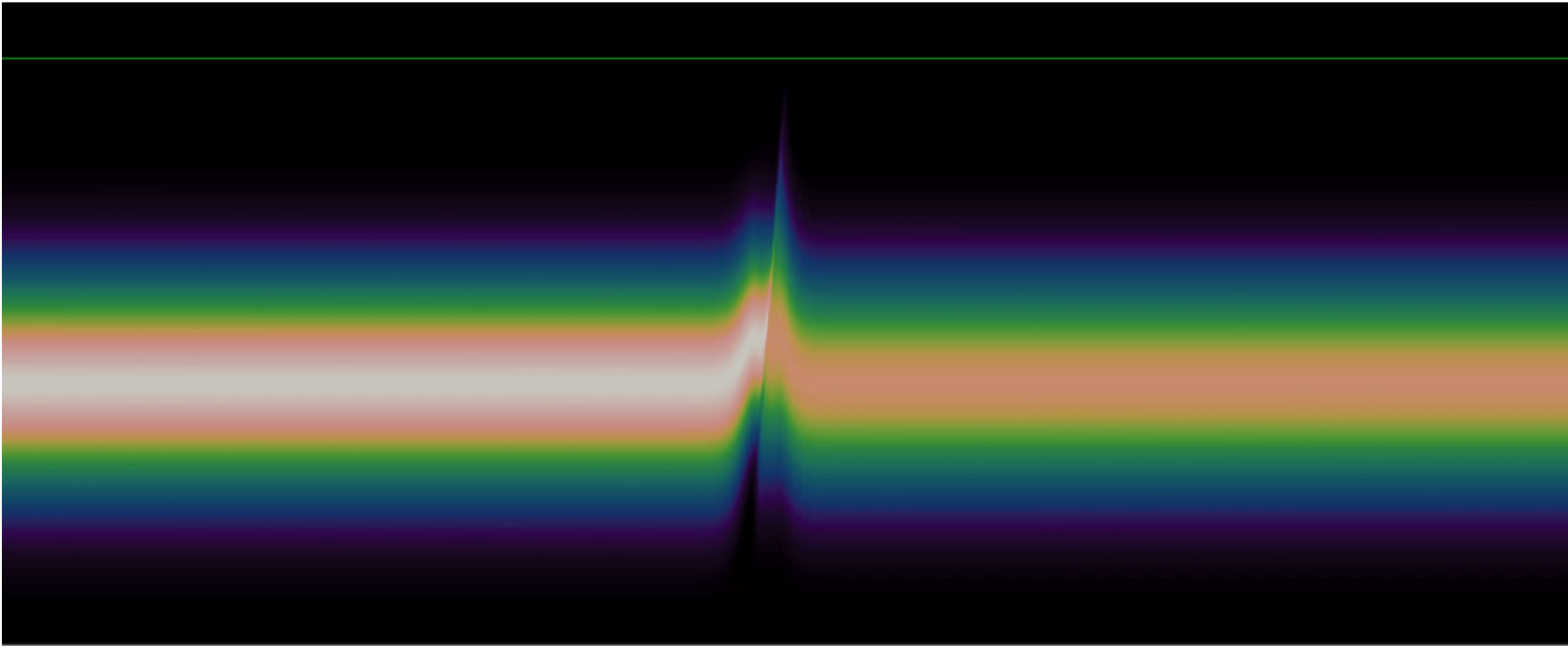

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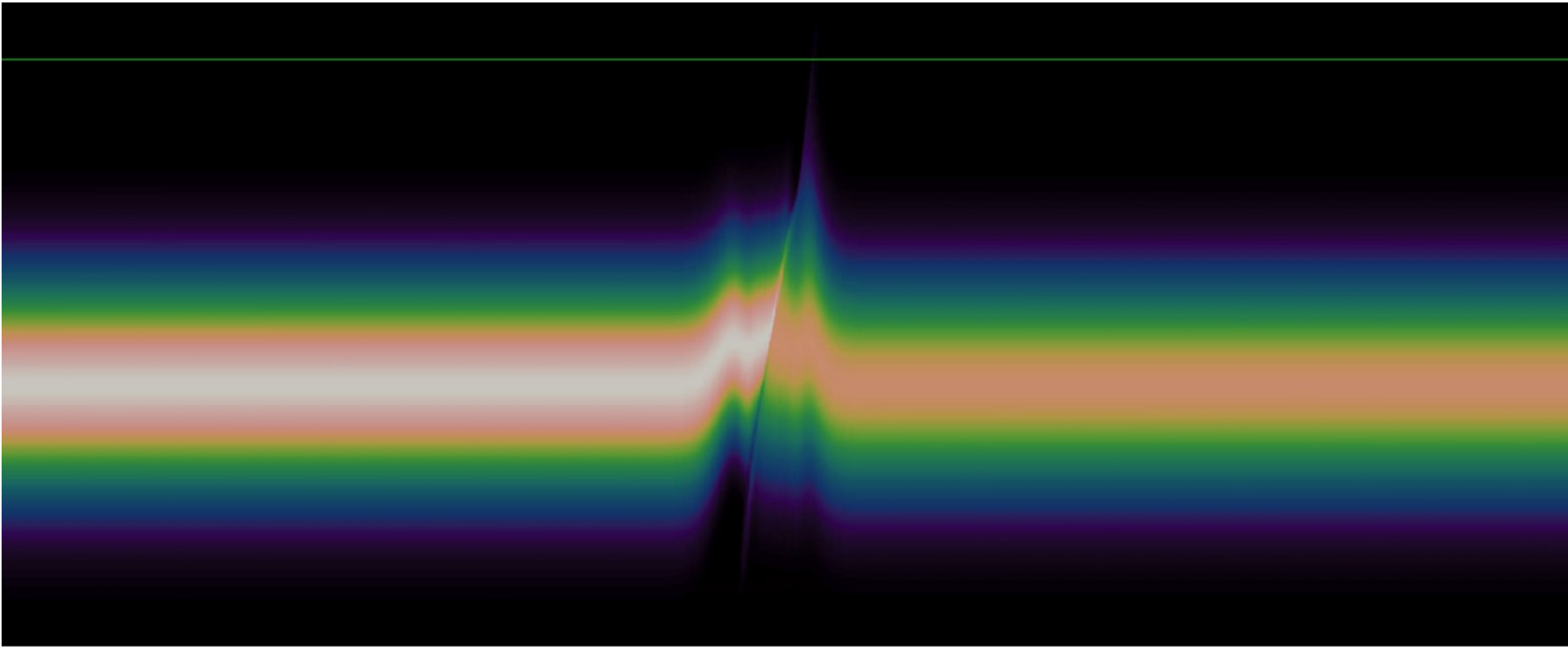

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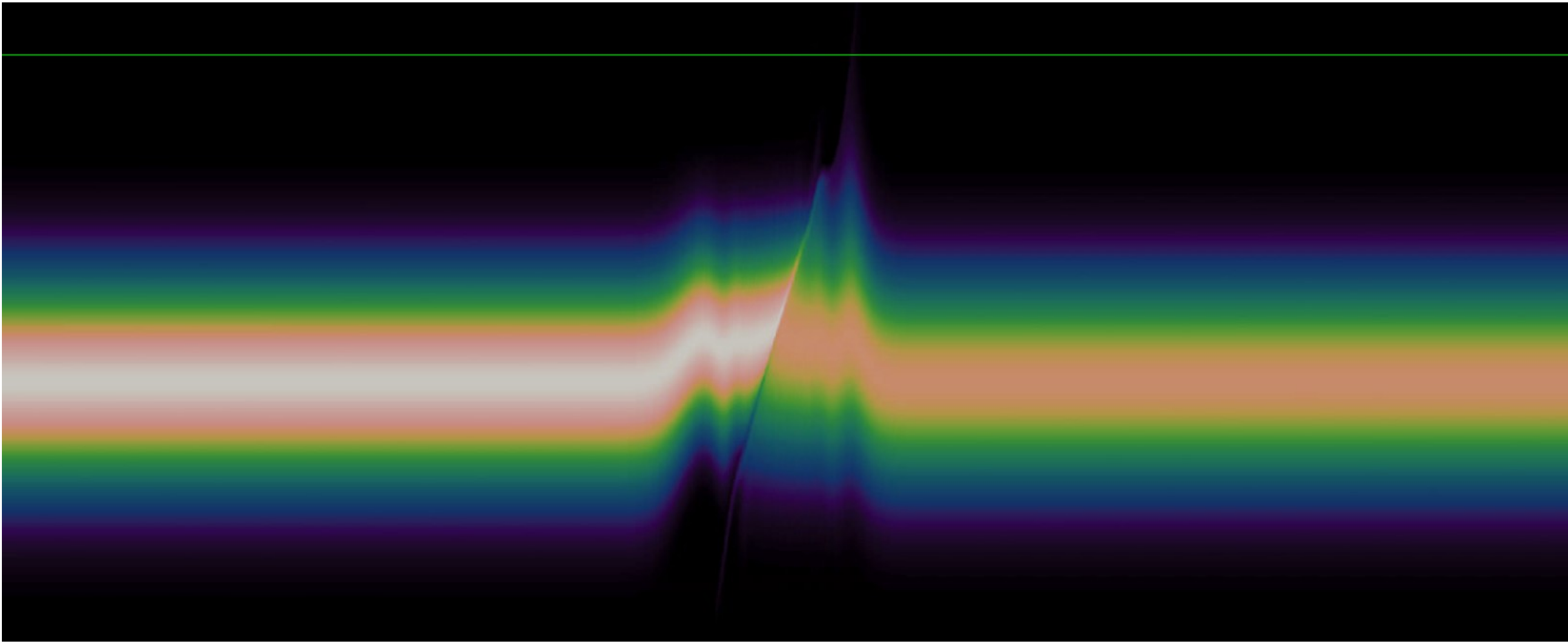

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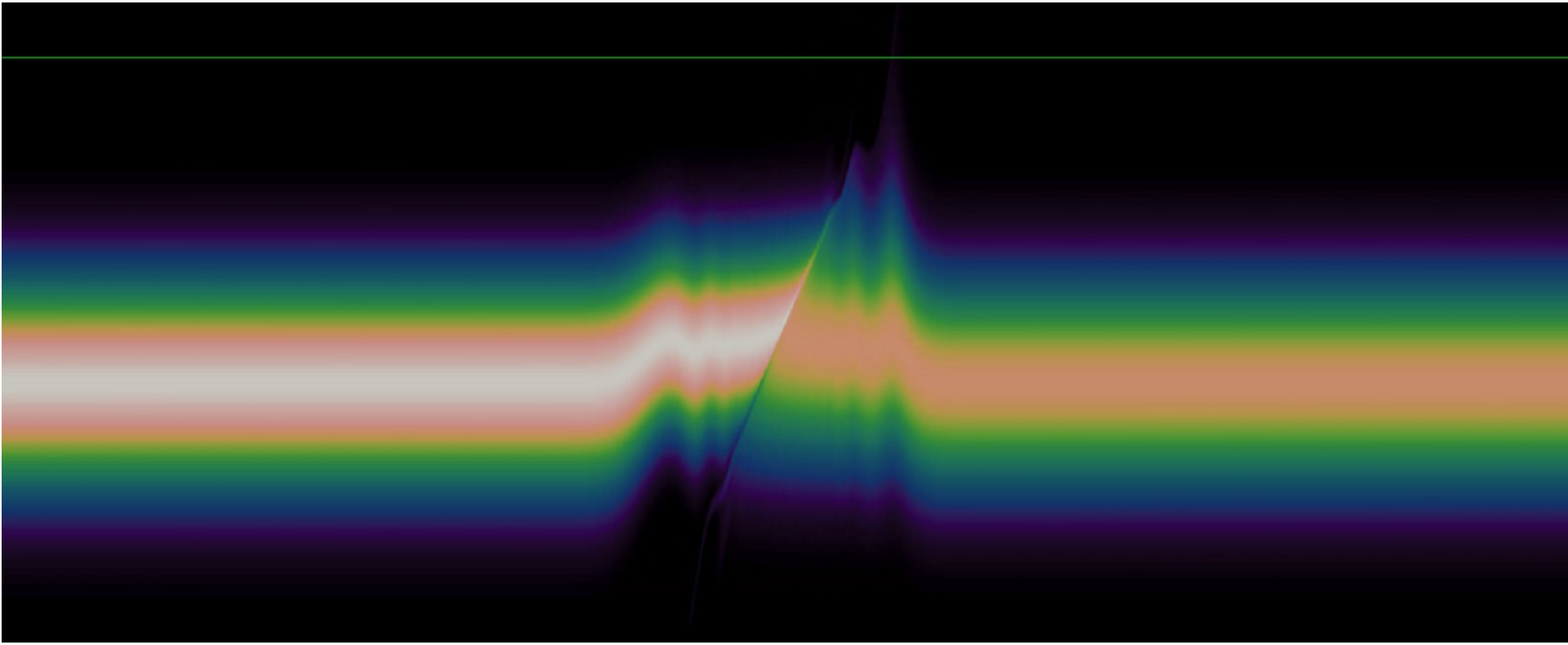

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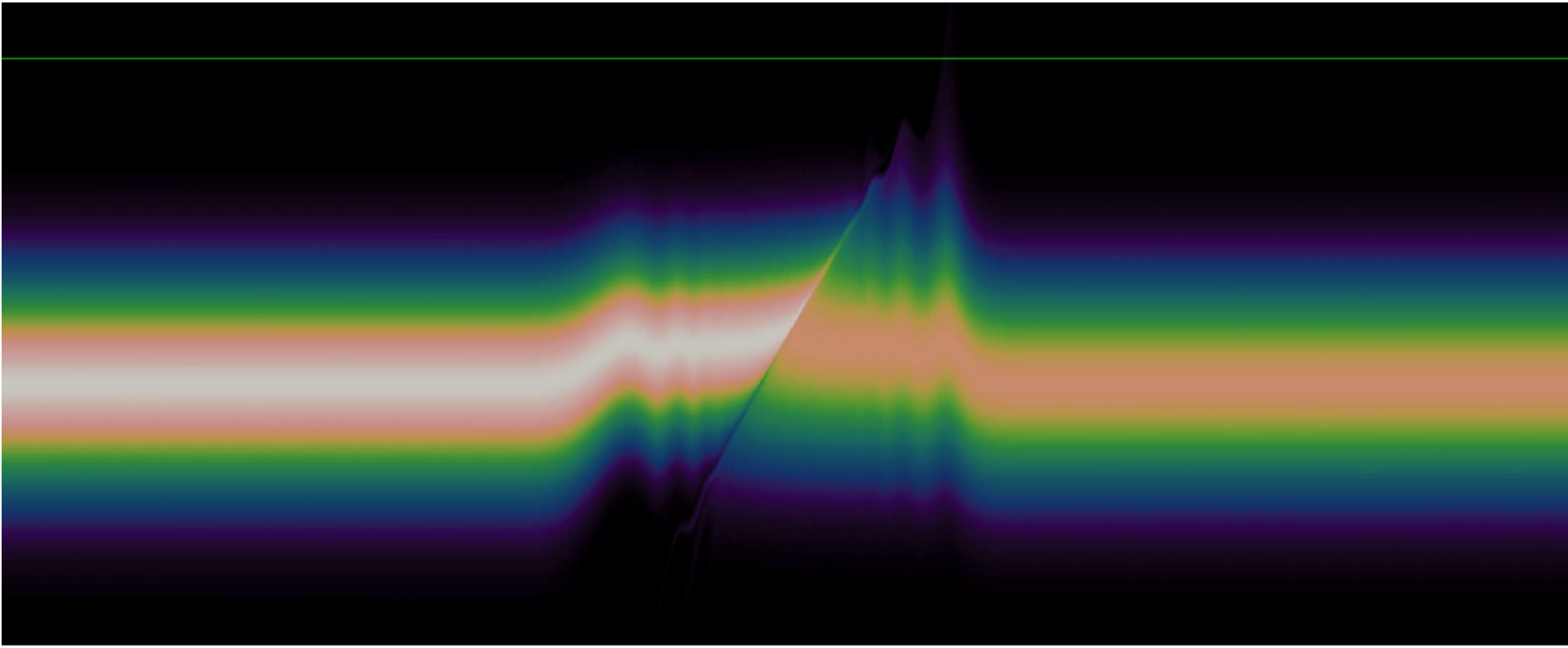

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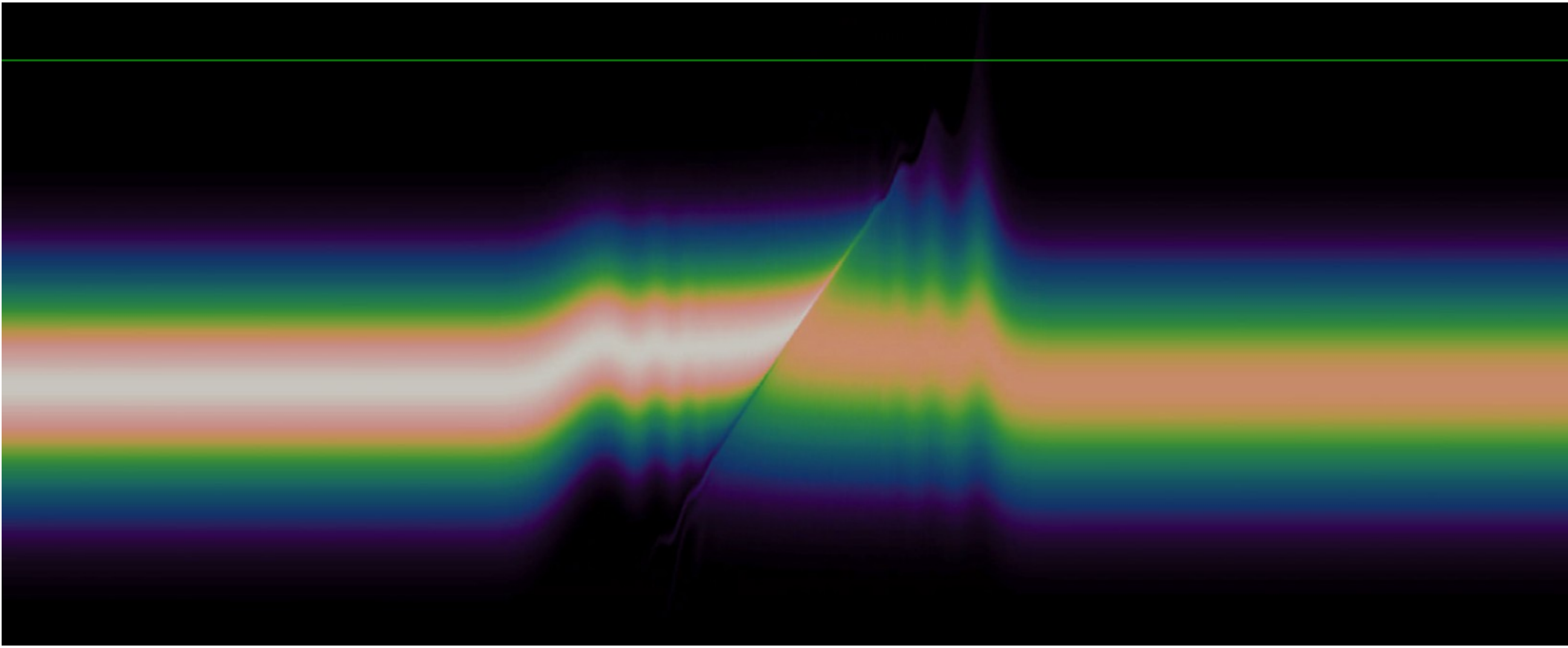

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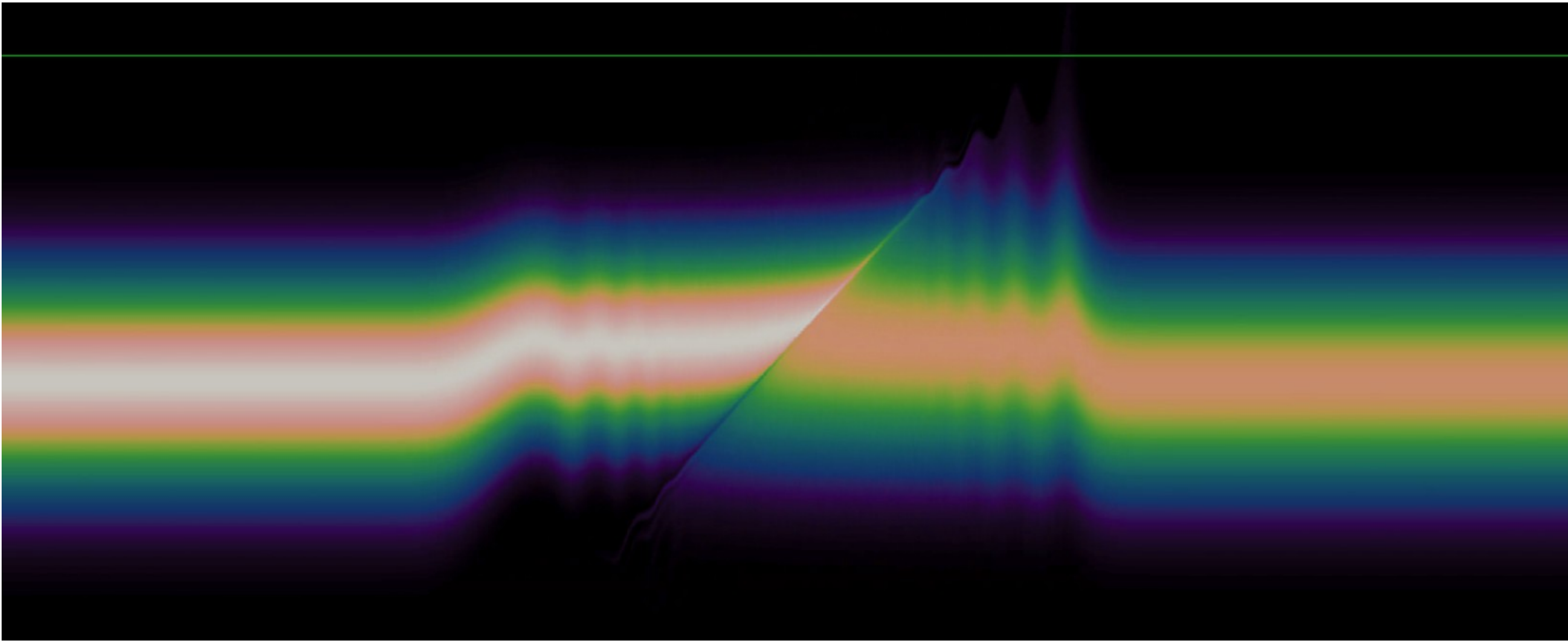

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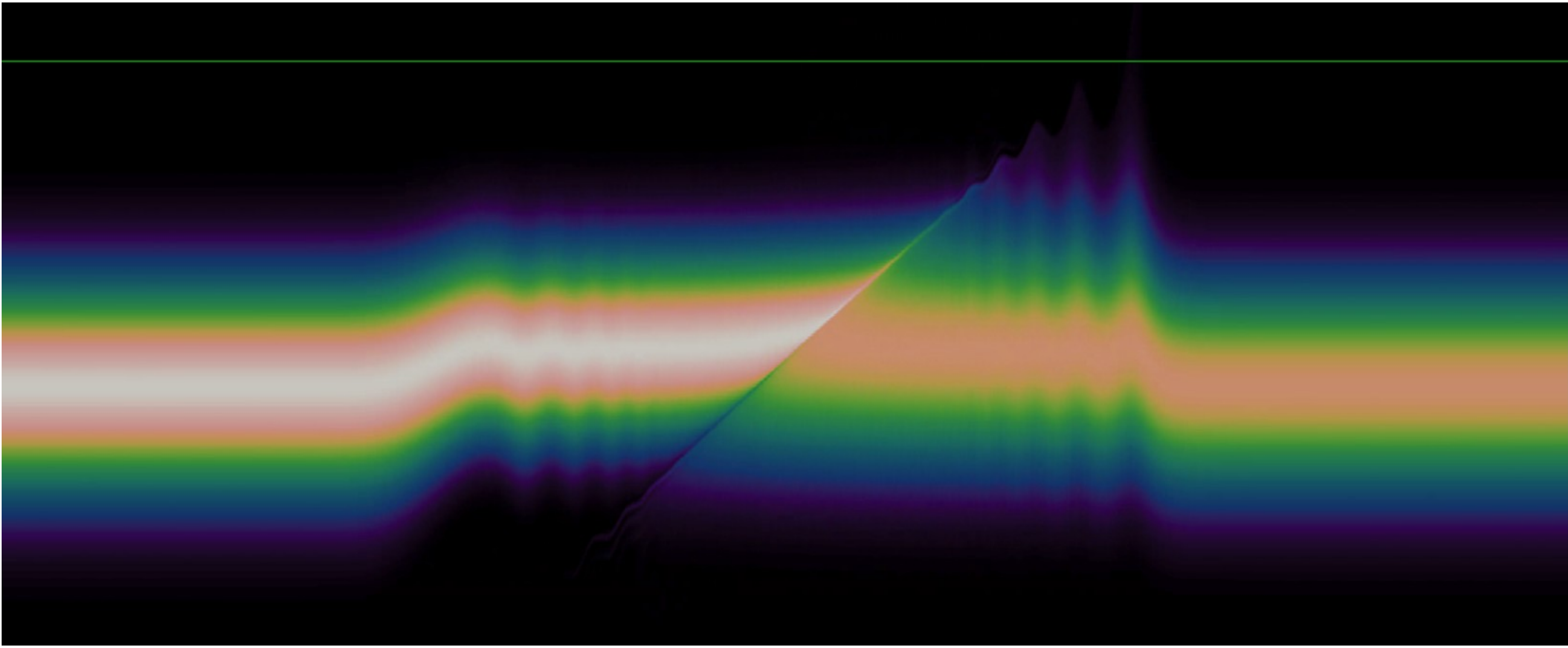

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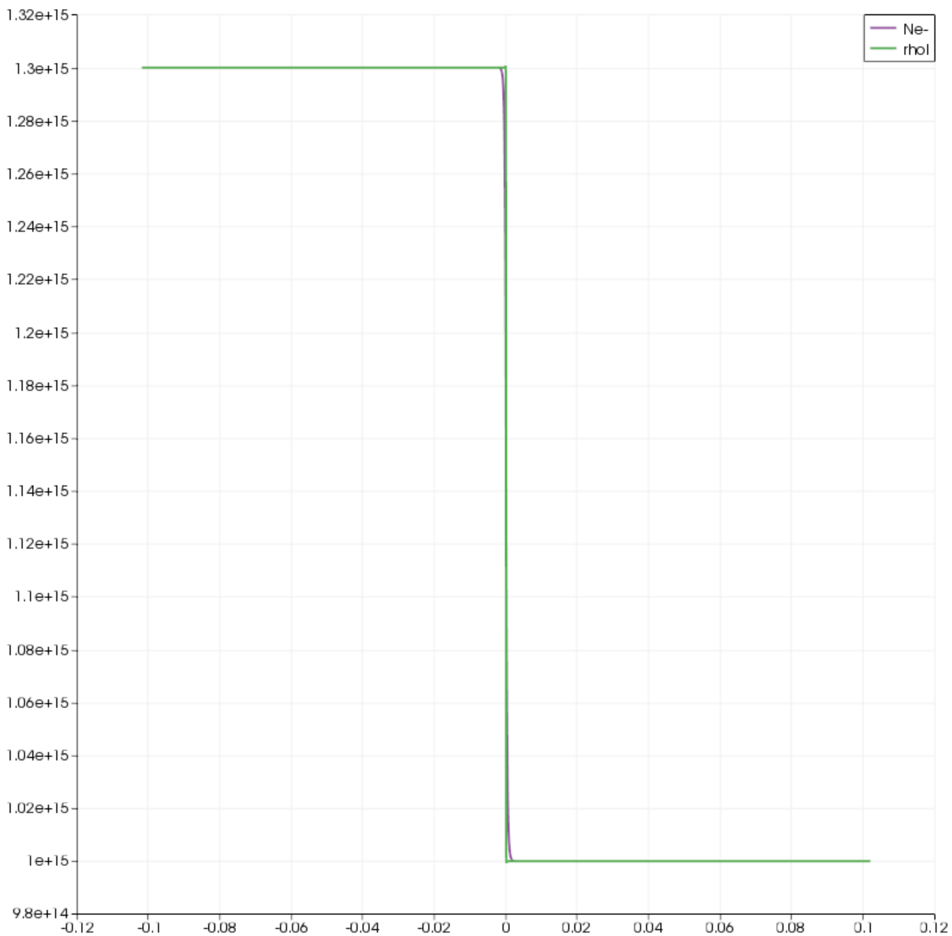
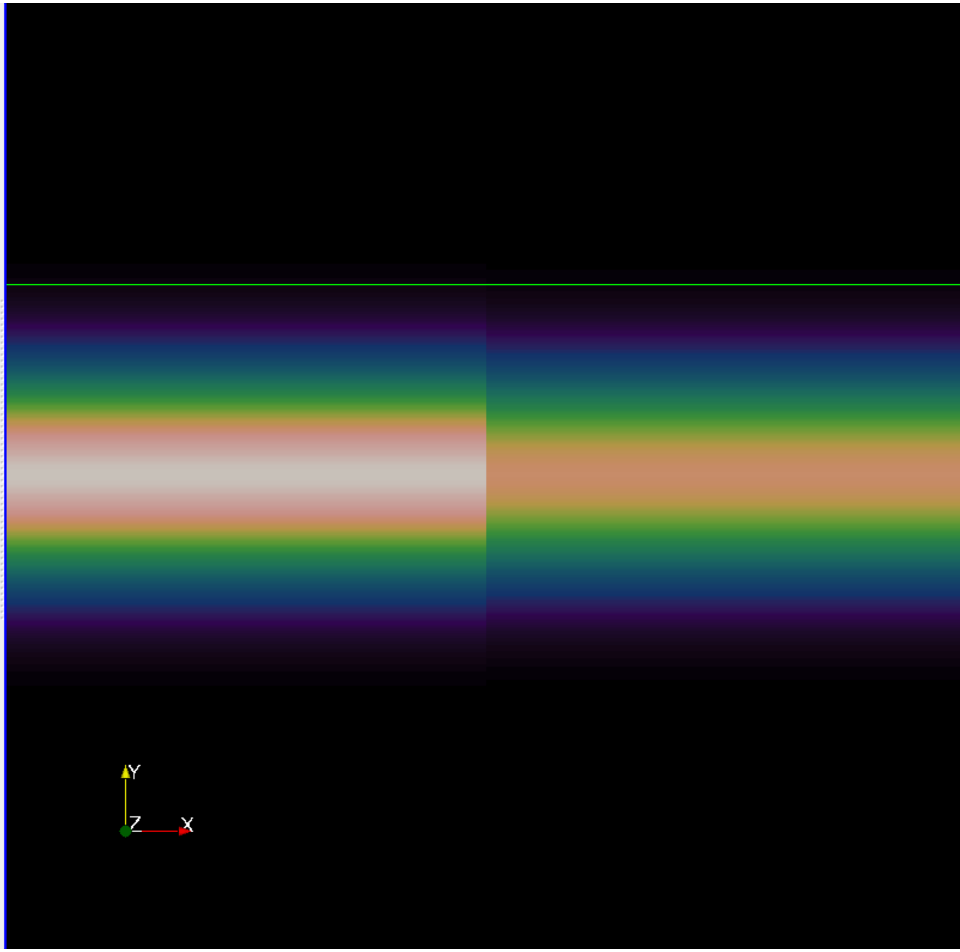
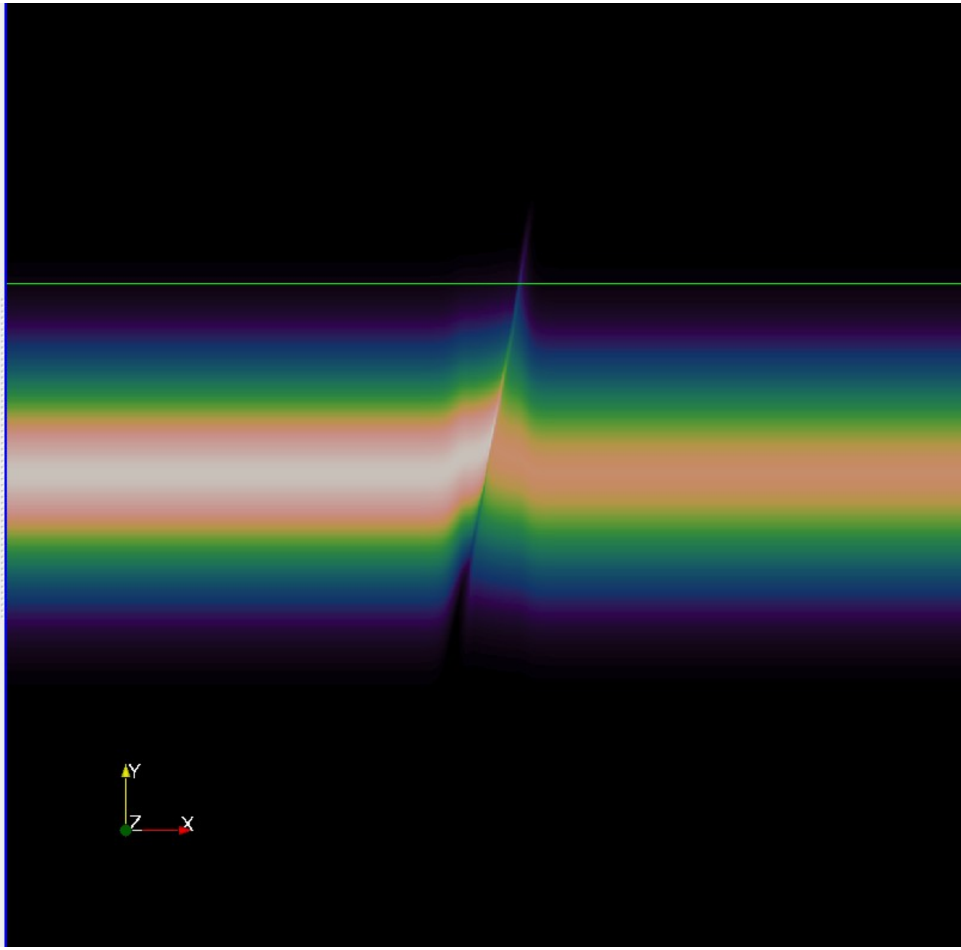




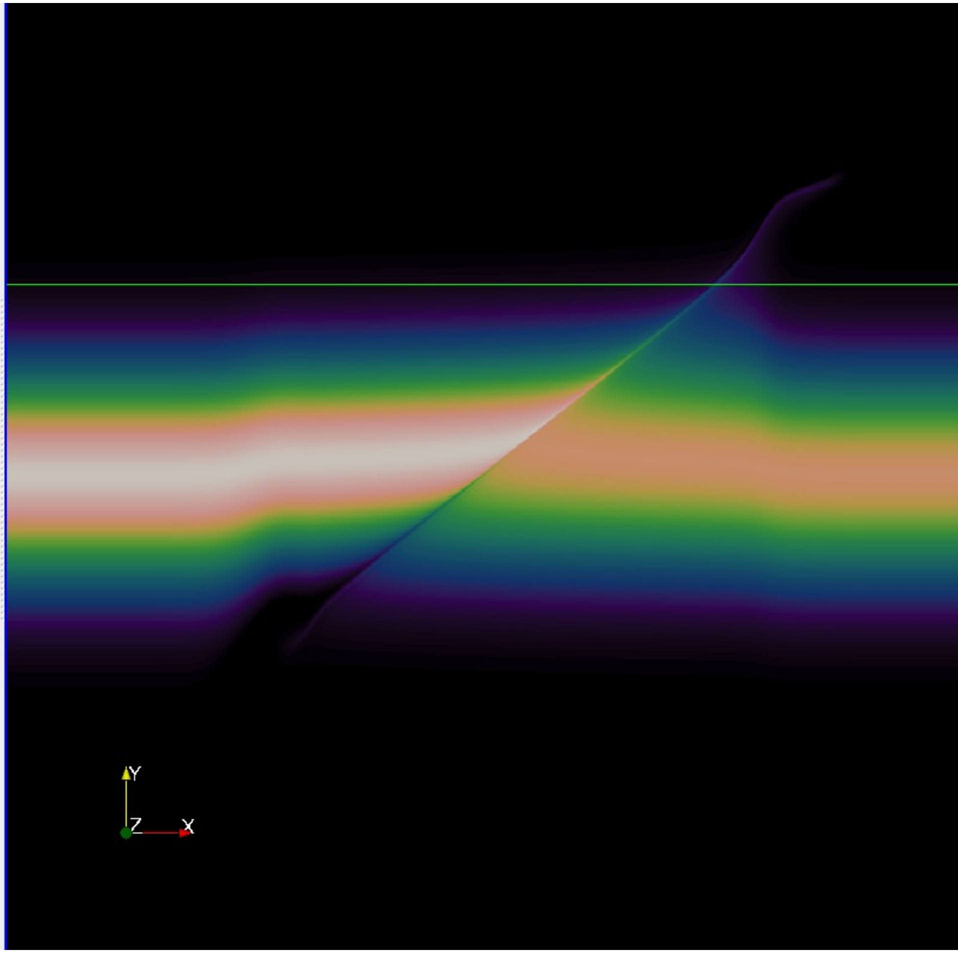
Heavily Damped Case
Electron Temperature: 1.5 [eV] | (Te/Ti =7.5)
Density Difference: 30%

Typical Simulation Result



Heavily Damped Case
Electron Temperature: 1.5 [eV] | (Te/Ti =7.5)
Density Difference: 30%

Typical Simulation Result



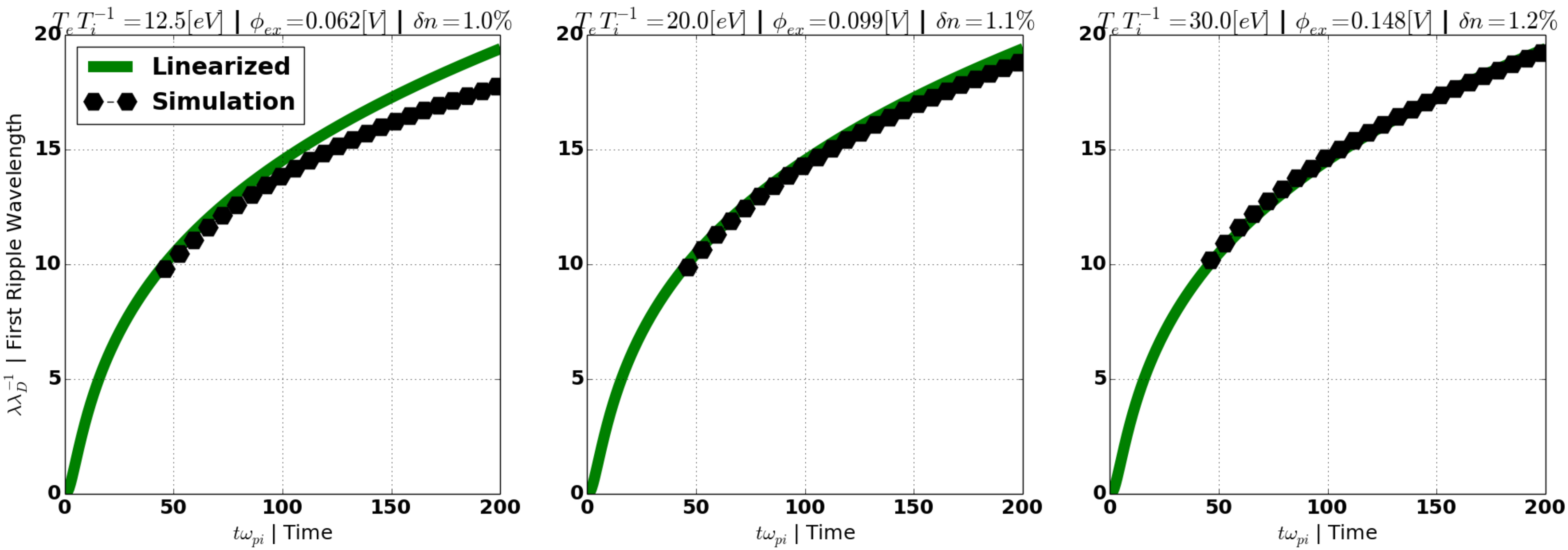
Heavily Damped Case
Electron Temperature: 1.5 [eV] | (Te/Ti =7.5)
Density Difference: 30%

Model Verification

Comparison with Linearized Solution

– **Evolution of the First Ripple Wavelength**:

- **Simulated weak shocks (1% jump) for different temperature ratios.**
- **Greater ion reflection at lower electron temperature alters the first ripple.**
- **Agreement improves with hot electrons, as ion reflection decreases.**

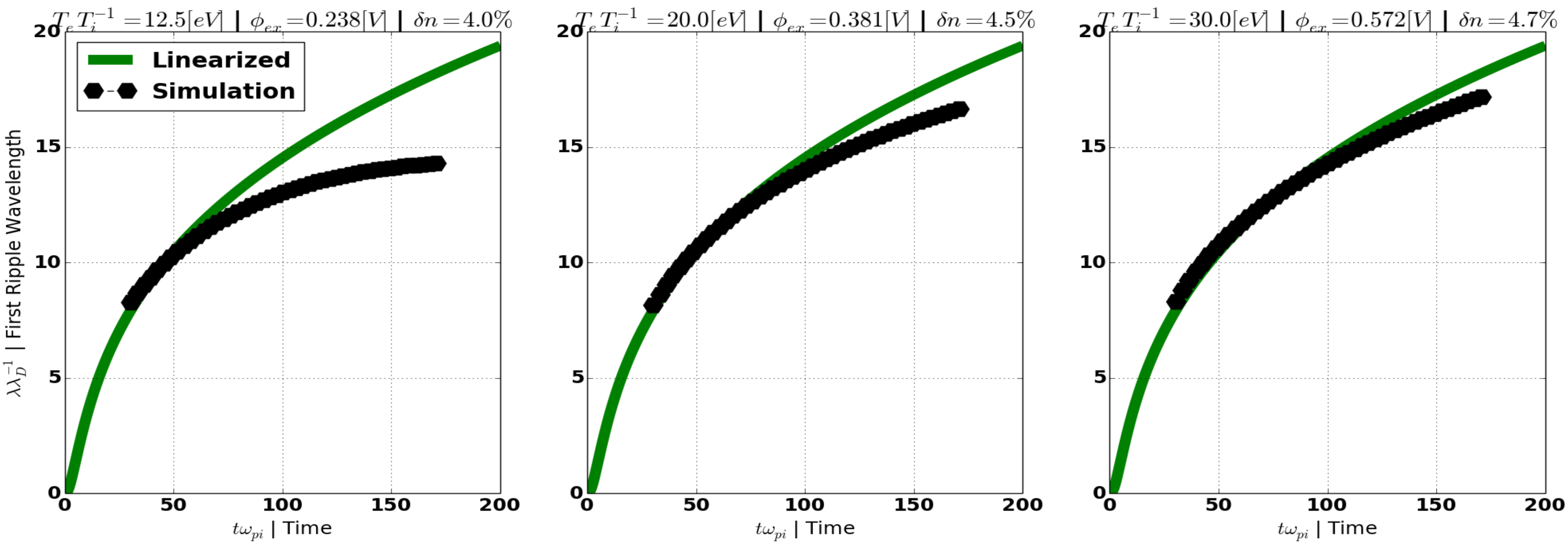


Model Verification

Comparison with Linearized Solution

– **Evolution of the First Ripple Wavelength:**

- **Stronger shocks (4%) show poorer agreement at lower electron temperature.**
- **Stronger shocks reflect more ions, causing stronger dissipation.**
- **Agreement with linearized model improves with electron temperature.**

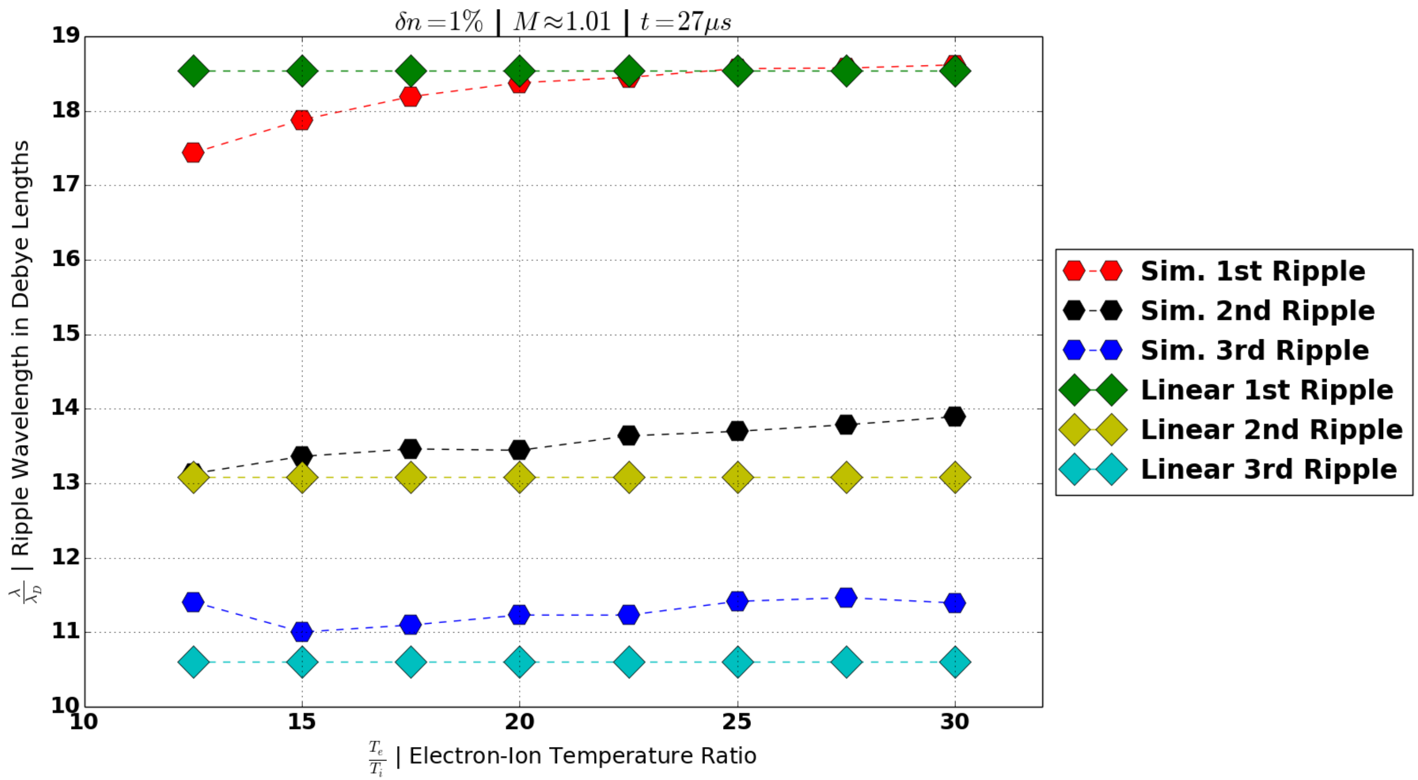


Model Verification

Comparison with Linearized Solution

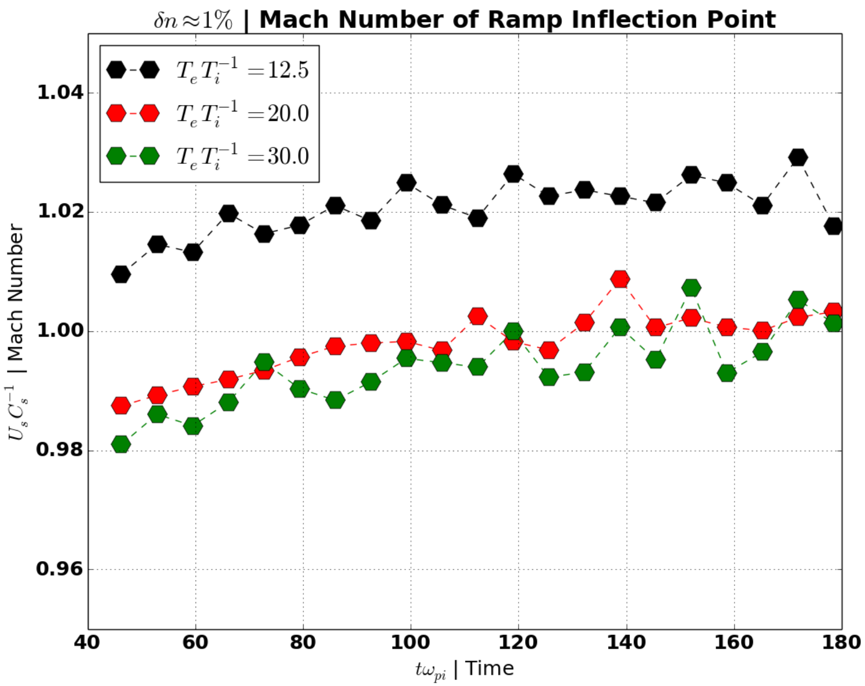
– **Trailing Ripple Wavelengths**:

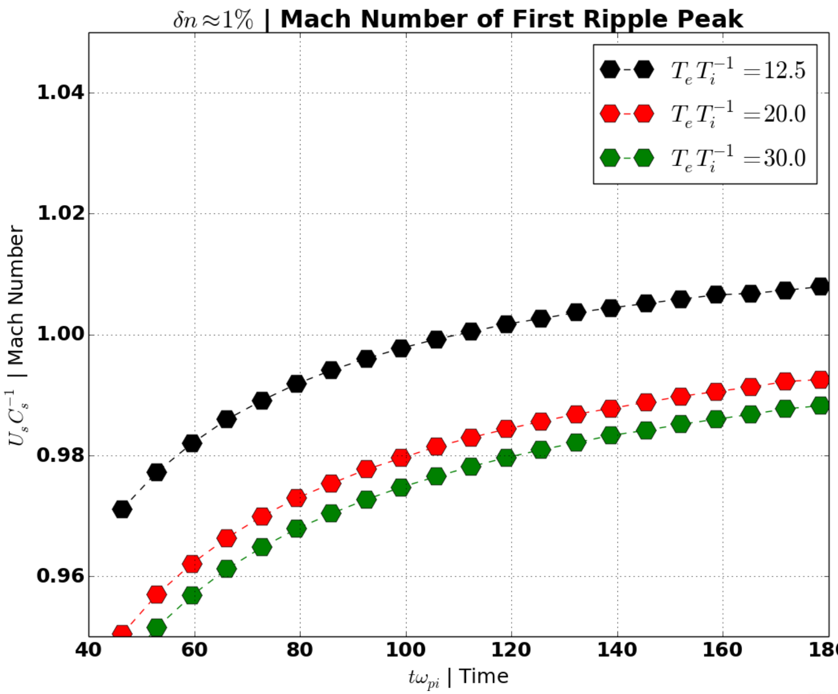
- **Subsequent wave train ripples diverge from the model.**
- **Simulated ripples do not approach zero wavelength like the linearized model.**



Other Weak Shock Results

- **Shock Mach Number**:
  - **For the same density jump (1% here),**
    - **Shock speed increases with electron temperature, Mach number decreases.**
  - **The first wave train oscillation peak travels less quickly than the shock ramp.**

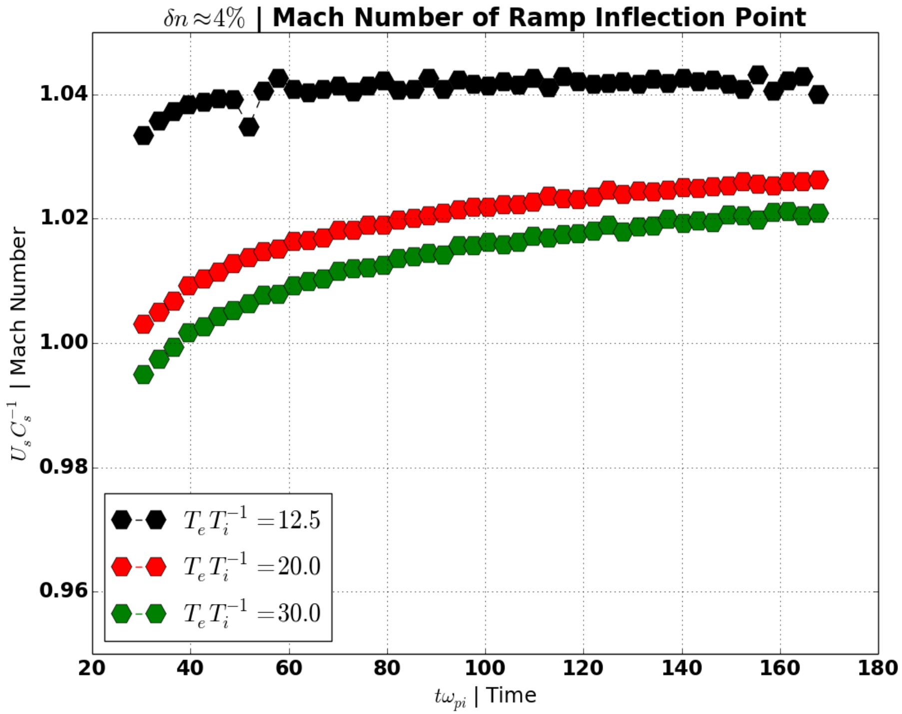


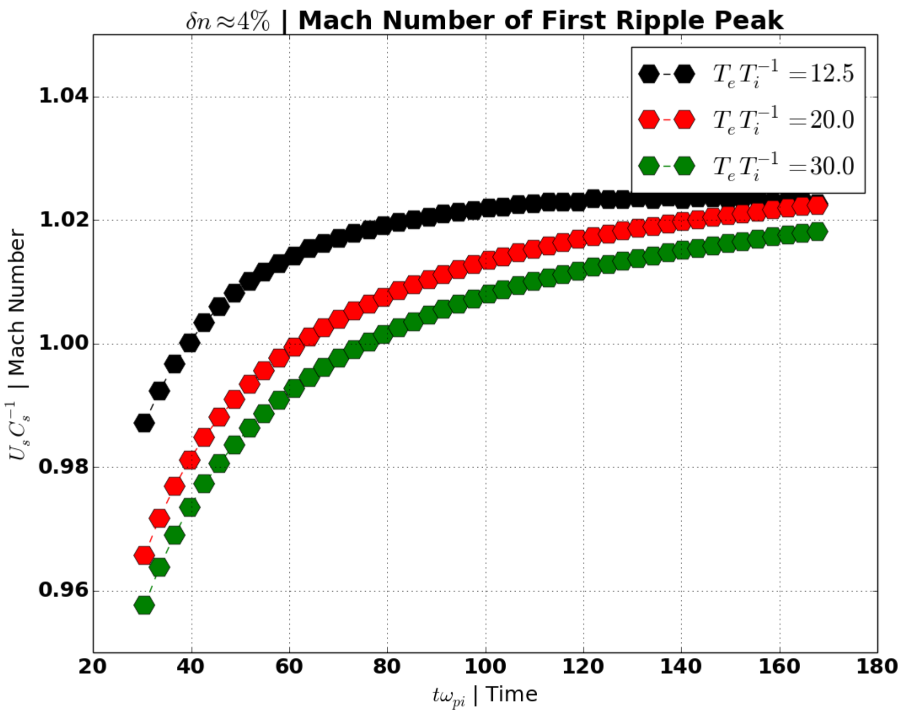


Other Weak Shock Results

– **Shock Mach Number**:

- **The same trends are apparent for slightly stronger shocks (4% jump here).**
- **Ion reflection appears to damp the shock acceleration.**





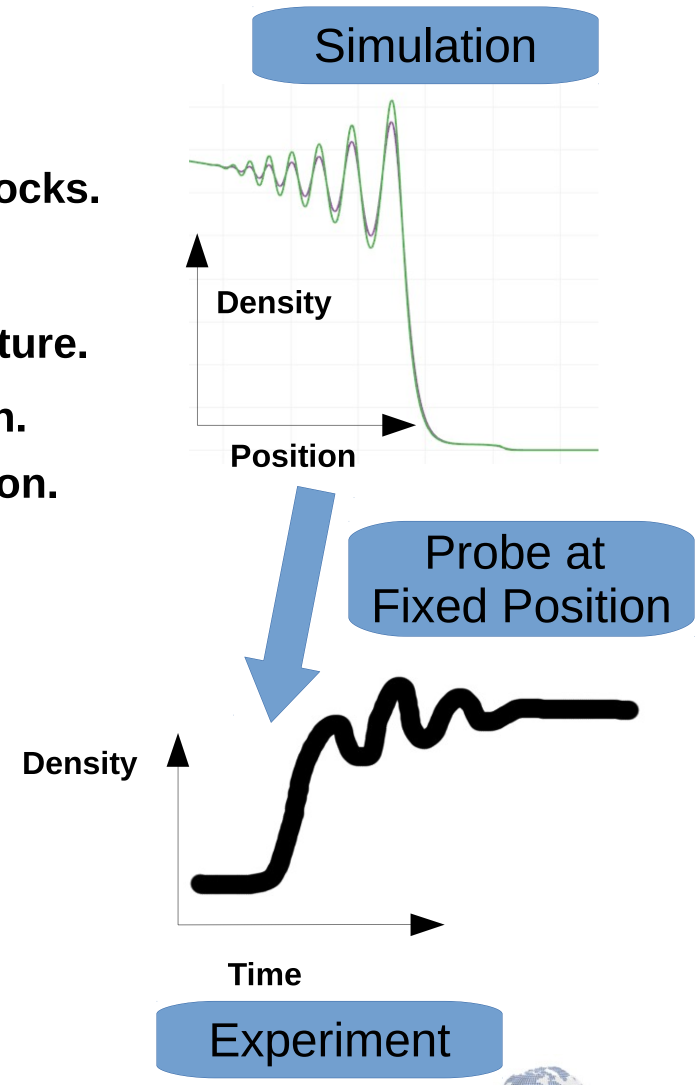
Model Validation

Gathering Experiment Data

- **Double Plasma Device**:
  - **Can produce low Mach number collisionless shocks.**
- **Diagnostics**:
  - **Langmuir probes; density and electron temperature.**
    - **Shock speed, and density at fixed position.**
  - **Ion temperature is necessary for proper validation.**

Validation Comparisons

- **The Wave Train**:
  - **Simulation suggests ripples should occur for:**
    - **Moderate Mach numbers (~1.2 – ~1.6)**
    - **High electron-ion temperature ratio (>10)**
- **Wave Train Wavelength**
- **Shock-Front Mach Number**
- **Reflected Ion Beam Velocity**



Towards Validation and Extension

Towards Validation of Collisionless Model

– **Verification**:
  - Simulated weak shocks agree with the linearized cold-ion solution.
– **Validation**:
  - Results should be compared to experimental shock data.
  - Inconsistencies in published 1969 double-plasma device data hampered validation.

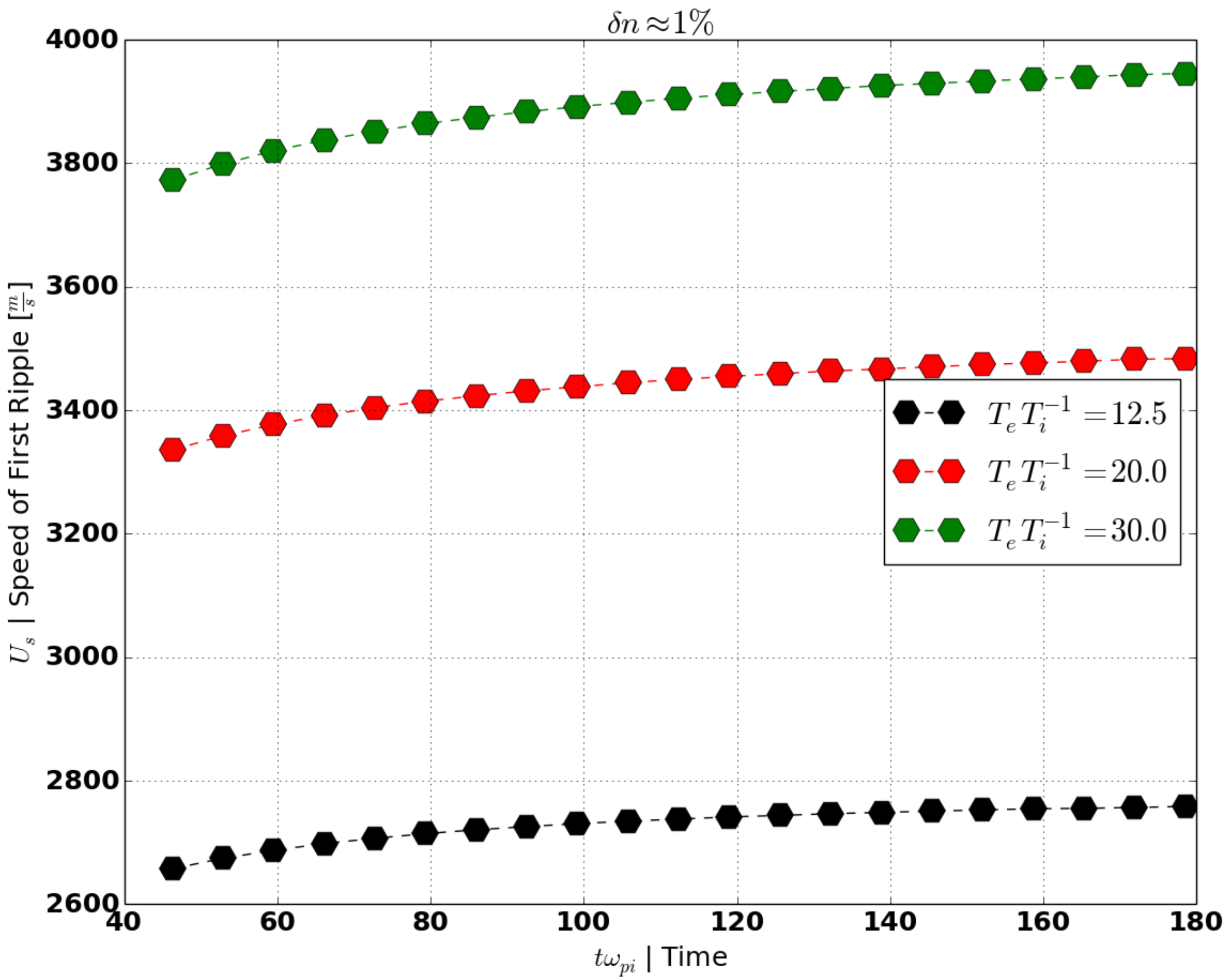
Future Work: Extension to Moderately Collisional Problem

– **Collision Operators**:
  - Presence of a few mean collisions in shock transition invalidates Vlasov equation.
  - The collisional ion-acoustic shock requires the full Boltzmann equation with appropriate choice of collision operator.
  - Moderately collisional shocks should be hybrid dispersive-dissipative shocks.
– **Validation of Collision Algorithms**:
  - Tuning parameters in a shock experiment can yield moderately collisional data.

Back Up Slides

Results on Shock Structure

Example of Shock Speed at 1%



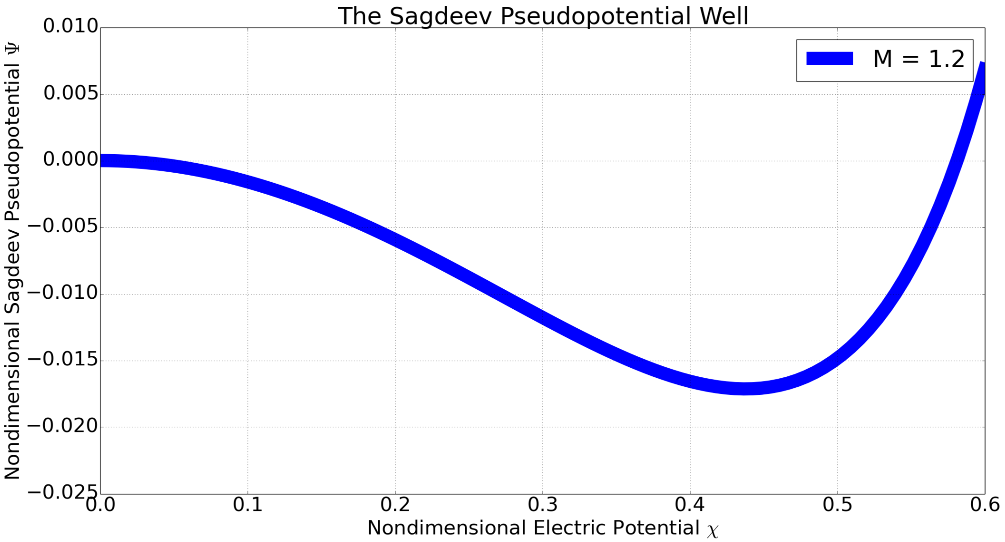
Details on Shock Structure

Wave Train Properties

- **Sagdeev Pseudopotential:**
  - **An analogy to motion in a potential well, describes oscillations in wave train.**
  - **Dissipation within the well leads potential to settle at the minimum.**

$$\frac{d^2\chi}{d\xi^2} = -\frac{dV(\chi)}{d\chi}$$

$$V(\chi) = 1 - e^{\chi} + M^2\left(1 - \left(1 - \frac{2\chi}{M^2}\right)^{\frac{1}{2}}\right)$$



Electric Field Details